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# DIASTROPHISM AND THE FORMATIVE PROCESSES

## XV. THE SELF-COMPRESSION OF THE EARTH AS A PROBLEM OF ENERGY

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The discoveries of the last three decades have led to new views of the constitution of matter, new evaluations of cosmic energy, new estimates of evolutionary rates, and new concepts of the time factor generally. Nearly all the fundamental concepts of geology need some degree of revision in the light of these radical advances. Among the rest there is need to rectify the concept of the earth's compression.

### THE CONCEPT OF COMPRESSION IN THE LIGHT OF NEW CONCEPTS OF MATTER

So long as matter was supposed to be formed of minute irreducible atoms, it was logical to assume that when these atoms were pressed into contact there was an end of compression. It was also quite natural to build upon this mechanical concept a merely mechanical notion of the process of compression. The new discoveries, however, lead to the view that the atom is a highly dynamic organization, a complex revolutional system, carrying within itself prodigious stores of energy and a structure as open as a planetary system. The materialistic factors—if

indeed they are really materialistic at all—recede to minute points, and do little more than play the part of carriers of electric charges. The prodigious energies of the atoms seem to be stored in the extremely rapid revolutions of these charged integers and in the fields of force and the polarities which arise from them. The atom itself and all the combinations into which it enters are therefore to be regarded as theoretically compressible to an undefined degree. The old assigned limit vanishes, and no new one takes its place. For aught that is now known, even the nuclei, or protons, and the electrons may themselves be composite dynamical organizations and subject to compression. The fact that a nucleus has a mass 1,800 times that of an electron suggests that perhaps analysis has yet one or more steps at least to take. Compression is therefore to be pictured as the struggle of one phase, or one set of phases, of energy against another phase, or set of phases, of energy, both sets being embodied in motion.

While perhaps it cannot yet be said to be strictly proved that the positive and negative charges are in revolution about one another, there seems to be no other way in which the prodigious energies associated with them can be stored without giving such evidences of themselves as characterize the non-revolutionary activities, distinctions to be considered later. Moreover, the notable successes of the revolutional hypotheses in accounting for observed phenomena leave little room for doubt that they are substantially true, and may be taken as a fairly safe working-basis.

In addition to the evidences of the atoms themselves, the analogies of the larger units of the cosmos lend support to the view that the atoms are revolutionary organizations.

### THE CONTRASTED MANIFESTATIONS OF ENERGY

In the great stellar field, where the largeness of things makes visualization easier than in the hidden ultra-microscopic world within, energy manifests itself in two rather distinct kinds of activity. The one is continuous motion in cyclic orbits or spiraloid revolutions running on indefinitely without loss of energy. It is, therefore, conservative and singularly undemonstrative. In the other, the motion is habitually interrupted by reversals and so is

discontinuous and disjunctive, giving rise to diversions and scatterings of energy in oscillatory radiations. This vibratory phase of activity is at once dissipative, agitative, and demonstrative. It has a general destructive tendency, while cyclic motion has a general constructive tendency. However, by weakening old structures, vibratory action prepares the way for new construction. The two types are therefore co-operative as well as antagonistic. The vibratory type has its chief manifestation in the heat-light-X-ray series; the cyclic type, in the planetary-stellar revolutional systems, and in atomic, molecular, and crystalline organizations. In application to material substances, the revolutional type is predominant in atoms, molecules, crystals, and true solids generally; the vibratory type is most manifest in the true fluidal states; in a special sense it may be said to dominate gases.

### THE RELATIVE ENERGY-VALUES OF THE TWO TYPES

In the ultimate analysis of all the cosmic states taken together, the revolutional type greatly preponderates in energy-value. This is not in accord with our sense-impressions. It is a rather singular fact that the values of these contrasted phases of energy are inversely proportional to their *obtrusiveness*. Neither rotations nor revolutions are notably demonstrative, while potential energy of position is only visualized by a mental effort, if visualized at all. The rotation of the earth involves a motion of a fraction of a mile per second; its revolution involves a mean motion of 18 miles per second, while its potential energy of position has a value of 356 miles per second. In this only relations to the sun are included; relations to the rest of the cosmos, in which further great, but only partly known, stores of energy are involved, are neglected.

Over against these great but unobtrusive forms of the earth's energy, stand the very impressive vibratory energies of the heat-light-X-ray series, the specially obtrusive and spectacular energies of the cosmos. While the precise sum total of these cannot be given for lack of adequate data, an excessive estimate may easily be made, and this will serve as a limiting value. According to Lane's law the highest temperature of a condensing body occurs at the stage when it is passing from the gaseous to the liquid state.

Let this stage be assigned the earth in its early history to give it a maximum value of the agitative type of energy. It must then of course have extended far outside its present solid surface. The parabolic velocity—the velocity that carries to infinity—at the present surface, is 6.95 miles per second. It is obvious therefore that the mean velocity of the molecules of the earth-substances could not have been so high as this without dissipating the earth. The maximum mean velocity of the earth-molecules must, therefore, always have been appreciably lower than 7 miles per second. We have, therefore, as the respective mean velocities, something less than 7 miles per second for the vibratory energy, something more than 18 miles per second for the revolutional velocity and—neglecting the rotational velocity altogether—356 miles per second for the potential energy. As the mass is the same in all cases, the energy-values are as the squares of these figures. Reduced and combined, the ratio of the vibratory energy of the earth, on the most generous allowance, cannot be more than 1/2600 of that of the revolutional energy, even when a large factor is neglected. The purpose of this comparison is to show the exaggerated importance that has been given to the agitative phases of energy, as also to the gaseous state, in the study of the earth's energy-values. In this, however, we have only considered the megascopic motions of the earth. We have yet to consider the ultra-microscopic phases in which prodigious energies are even more unobtrusively concealed.

To approach the ratio between the dissipative and the constructive classes of energy in the earth-matter itself, let the familiar case of a bowlder on the surface be taken. Let it have the mean temperature of the earth's surface, say 15° C. Its absolute temperature will then be about 288 centigrade degrees. This represents a linear extension of about .0057. All the rest of its extension represents the work of constructional energy—here interpreted as revolutional energy—except the space occupied by the atomic nuclei and the revolving electrical charges. While the total value of the energy of the revolving constituents of the atoms is undeterminable at present, it is certain that it is almost incomparably greater than that of the 288° C. temperature.

When this atomic energy, which is even more unobtrusive than the energies of celestial revolution, is added to the macroscopic energies, the disparity mounts up to a very high figure. The agitative energies that so deeply impress our senses are really little more than trivial, relatively, in the true cosmic scale.

Now, the resistance that is offered to the compression of an earth made up of solid matter springs mainly from the forces that determine the constitution of this matter. The analysis of these constitutional energies, as now interpreted, involves the electronic revolutions, together with the fields of force and the polarities that spring from them. These may not be all the forces involved—very likely they are not all—but they form the truest picture now available and they may be taken as representative. They are herein made a working-basis, subject to correction as additional light is disclosed.

### THE RELATIVE ENERGY-VALUES OF THE POSTULATED EARTH-FORMING NEBULAE

In estimating the potential energy of the nebular matter which, by hypothesis, was condensed to form the earth, in each of the two representative views, the planetesimal and the gaseous or quasi-gaseous, it is assumed, in both cases, that the earth was formed in essentially its present position and relations in the solar system.

In Article XIII of this series,[1] a conservative estimate of the belt occupied by the planetesimals that were later to form the earth, gave it a space-value of $9\times10^{23}$ cubic miles. The gaseous nebula that was to form the earth, measured at the time it first came into self-control and was most extended, had a volume less than $3.5\times10^{18}$ cubic miles. The ratio is about 250,000 to 1. The vastly superior space occupied by the planetesimals, however, does not carry proportional value in potential energy. Its importance chiefly lies in the mode of support of the planetesimals and in their modes and rates of assemblage.

### CONTRASTED MODES AND RATES OF ASSEMBLAGE

The modes of concentration were radically different. The planetesimals were sustained in their orbits by velocities of a

[1] *Jour. Geol.*, Vol. XXVIII (1920), p. 678.

mean value of about 18 miles per second. Thus sustained, they only joined the collecting nucleus as variations in their orbits brought them into conjunction with it—a slow process, occupying perhaps two or three billion years.[1] The intervals between the infalls of the planetesimals were, therefore, such that nearly all the heat of their impact with the atmosphere and with the earth's surface was lost before they were buried by added material. The growth of the earth was thus made by the slow accumulation of essentially cold, solid particles mixed at random.

On the other hand, if the earth-forming nebula be assumed to have been gaseous and to have descended along the gaseous line, its volume was sustained by collisions and rebounds of the constituent molecules, and it contracted as fast as the loss of this interaction, i.e., the loss of heat, permitted. Under Lane's law the maximum temperature was reached at the stage when the gaseous body passed into the liquid state. As radiation follows the law of the fourth power, the collapse was relatively rapid; at the most it cannot be assigned more than a few million years.

Enormous losses of energy would be suffered in either the planetesimal or the gaseous mode of assemblage, and so we must take up the question of the earth's primitive energy presently from the opposite point of view: What energy-values were *left* for the evolution after the earth was able to make a record of its own compression? The point of most importance here is the radical difference in the respective factors that controlled the self-compression which followed the nebular concentration. It is obvious that the gaseous descent was controlled by *heat* and that this remained the master factor in the shrinkage of the earth after it became a white-hot molten globe. In the self-compression of the earth built of solid planetesimals, or planetesimal dust, *solidity* was the primary resisting-factor that held the compression in check. The energy-factors in this case were those to which the solidity was due. These are herein interpreted as revolutional phases of energy together with their derivatives. Heat in one case and solidity in the other were then the master factors in the

[1] See "The Rates of Planetesimal Infall," Article XIII, *Jour. Geol.*, Vol. XXVIII (1920), pp. 677 ff.

compression process. In the latter case, the heat generated in the course of the compression was secondary to the revolutional energies. The special courses taken by both the primary and secondary energies become therefore vital elements in the compressional process; to these we shall presently turn.

As indicated above, to form estimates of the energy-values that were inherited by the earth at the stages when it began to make its automatic record of self-compression, it is necessary to enter into a more specific analysis of its status in the two hypothetical cases.

## COMPARATIVE VALUES OF ENERGY AVAILABLE FOR DIASTROPHISM

The deformations of the earth are the most available test of the energies that entered into its self-compression, though by no means the only test. There is now no ground to doubt that the diastrophism was large, whatever estimate may be made of its precise value. There must have been enough energy in an available form to actuate the distortions involved, and this energy must have been properly distributed in time and place. The sources of this energy need therefore to be considered in respect to their availability, as well as their adequacy. Fortunately, the problem for all cosmological lines of descent seems to center in the alternative: Was the earth assembled in a fluidal condition dominated by heat, or was it built up gradually by accessions of small fragmental matter in a cool, solid, highly mixed state? If there are tenable hypotheses of an intermediate sort, the considerations that apply to these type-views can easily be adapted to them.

The chief energies available for the evolution from this point on, are (1) the residue of the potential energy of position, except of course what still remains potential; (2) chemical and physical combinations, readjustments, and reorganizations, so far as conditions permitted them to take place during the compression; and (3) the disintegration of radioactive substances, including any other changes in atomic constitution that may have taken place, if any. These atomic factors may possibly have some relation to the extreme stresses that arose from compressional action, but as

there is now no evidence of this, they must be treated under a head of their own.

1. *The period of compression.*—If the earth remained fluidal until all its rock-substance was condensed into a globe, none of the energy lost in the assembling was available for making the observed diastrophic record, since this could only begin after consolidation began. If, on the other hand, the earth was built up of small solid accessions loosely laid down, these must have begun to suffer compression and distortion as soon as one layer was laid on another. The distortional process must in this case have run on thence through the whole history of growth. The compressional and distortional actions were furthermore brought on very gradually and great lapses of time were available to meet the growing stresses by the resources of readjustment, reorganization, metamorphism, and diastrophism.

2. *Availability of the main compression.*—If the earth was assembled in a fluid state, the interior underwent the full measure of fluidal compression from gravitative action before it could make any diastrophic record; little more than the effects of cooling remained available for deformative work after solidification took place. If, on the other hand, the material of the earth was added slowly in a loose, solid state, the main compressive effects entered into the record; for while the distortions in the deep interior would never be accessible, they must have been at all stages the foundation on which the later accessions were built and hence they gave direction to, as well as participated in, the stress effects that arose at every subsequent stage in the increase of mass. They must still continue to participate in the effects of all the more general changes in gravity.

3. *Chemico-physical combinations, readjustments, and reorganizations.*—If the earth remained fluid and convective until fully assembled, almost ideal opportunities for chemical combination and physical adjustment, as well as chemico-physical reorganization, would have been offered, except in so far as the heat itself may have restrained such action. To this extent the chemico-physical resources should have been exhausted before they became available for diastrophism. But if the earth were built up of solid particles

of various sorts mixed by the chance of infall, it would offer almost ideal conditions for recombination, readjustment, and reorganization, which, in this case, would run hand in hand with diastrophism and contribute to it.

4. *Relative exhaustion of potential energy by segregation.*—If the earth was fluid until fully assembled, there should have been facilities for the arrangement of the earth substances in concentric layers according to specific gravity. This would have been a special means of reducing to the lowest terms the potential energy that might otherwise have remained available for deformative work after solidification made a diastrophic record possible. If, on the other hand, the matter remained a heterogeneous mixture so far as intrinsic heaviness was concerned, a corresponding amount of potential energy remained available for the diastrophic record. In so far as segregation by gravity took place during the compression of the mixed solid mass, it co-operated with other deformative processes and left its effects in the record.

5. *Relative exclusion or retention of gaseous constituents.*—If the earth remained fluid and convective until fully assembled, the gaseous constituents should have had favorable opportunities for escape and should have been impelled to escape by the very high heat, so that only such quantities as were required to balance the partial pressures of the same constituents in the atmosphere should have remained to take part in vulcanism later.[1] On the other hand, if the earth was built up by solid particles added slowly to the surface and subjected to weathering and to mixture with air and water, as it was gradually buried, the complex should have afforded almost ideal conditions for the evolution of volcanic gases when it was later subjected to heat and pressure. The phenomena of the moon are especially instructive in this respect, for the gravity of the moon is insufficient to hold free volcanic gases even in its present cold state; much less then in a hypothetical molten state. No equilibrium factor should have been retained in this case. But the evidences of vigorous explosive action on the moon are very pronounced.

[1] Rollin T. Chamberlin, "The Gases in Rocks," *Jour. Geol.*, Vol. XVII (1909), pp. 565–68.

6. *The distribution of the radioactive substances.*—If the earth were assembled in a fluid state, the radioactive substances should have settled toward the center because of their high specific gravity, or else, if convection prevented this, they should have been distributed sub-equally through the whole mass. There should at least have been no concentration of such heavy material in the upper layer. But the special investigators of the subject agree that if the whole earth were as rich in radioactive substances as its accessible portion is, the heat generated would be many times greater than the heat now conducted to the surface and radiated away. Were this true, the earth should have been growing hotter all through its history and no shrinkage at all could be assigned to cooling. On the other hand, if the earth were built up of heterogeneous clastic matter that carried its chance portion of radioactive particles, and if these, by their heating action, liquefied the most susceptible matter immediately enclosing them, and if such liquid matter were then squeezed to or toward the surface by the powerful extrusive agencies that belong to a solid earth, the radioactive substances would be concentrated in the zone of lodgment of these igneous portions. This limits the radioactivity to a degree that seems to fit the observed facts and the theoretical intimations of the case. It is quite obvious that, so far as deformative effects assignable to cooling are concerned, the hypothesis of a molten earth is seriously embarrassed by this newly discovered source of heat superposed on an already embarrassing inheritance of heat from its earlier history, while under the hypothesis of a cold-grown solid earth, it is a welcome agency.

The combined import of all the preceding considerations leaves the fluid earth embarrassingly short, if not fatally short, of resources of energy available for making the observed diastrophic record, while the planetesimal earth is much more amply, and apparently quite adequately, supplied with such energy, and this becomes available in such a slow way as to give great allowances of time for the increments of compressive stress to work out their adjustments and easements along metamorphic and diastrophic lines.

THE INTERCHANGES BETWEEN THE TWO BASAL TYPES OF ENERGY

Before taking up the special modes of the compressional process, the interchanges between the two basal types of energy need consideration. The constructional and the agitative phases of energy are not only interchangeable but interchanges are persistently taking place on the surface and within the earth, and these interchanges play a vital part in the process of the earth's self-compression. The proper recognition of these is indispensable.

Exchanges between thermal and mechanical energy are too familiar to need notice; they are a basal feature in modern industry. But exchanges between agitative and organizing energy, i.e., between vibratory and revolutional energy, as such, though they may not differ in essence from the well-recognized interchanges, need a word of emphasis. Some of these changes from the agitative to the constructive are even more familiar than the mechanical changes, but interpretation has not given them the value to which they are entitled. We know that the grass and the trees grow, but we easily overlook the fact that such growth is a widespread and important endothermal process. It belongs to the unobtrusive class and does not enforce attention. The prairie fire and the holocaust of the forest, the complementary exothermal process, command our lively attention. The unobtrusiveness of endothermal action is likely to deceive us as to the balance between interchanges of energy in nature. The problem in any special case is to determine the balance between opposing actions. There is, however, no doubt as to a real preponderance of exothermic action on the earth's surface. When lavas come up from below, they usually undergo exothermic reactions to a greater extent than endothermic reactions. This in itself raises the question whether endothermic reactions are not preponderant in the region whence the lavas come. Van Hise,[1] Leith,[2] and their associates, have shown by the extensive collection and study of data from the full

[1] C. R. Van Hise, "A Treatise on Metamorphism," Monogr. XLVII, *U.S. Geol. Surv.* (1904).

[2] C. K. Leith and W. J. Mead, *Metamorphic Geology*, Henry Holt and Co. (1915). See particularly the chapters on "Katamorphism" and "Anamorphism" in both works.

range of the accessible terranes, that while exothermic reactions preponderate in the outer or katamorphic zone, the preponderance is reversed below and endothermic reactions take precedence in the anamorphic zone. It is to be noted that while katamorphic action, exothermic action, and the lowering of density, commonly go together, as also anamorphic action, endothermic action, and rise of density, they do not invariably coincide; and further, that none of these necessarily excludes the others from any horizon. The essential question is not one of exclusive action but of preponderant action.[1] It is in the natural order of things that in the great contact zones between the atmosphere, the hydrosphere, and the lithosphere, there should be a trend of energy toward its agitative phases, and that in the stabler solid zones below there should be a compensating trend toward the constructional and the persistent, without limiting either zone to one type of action. In terms of the two basal types of energy, exothermic action, on the average, involves a change of organizing or revolutional energy into vibratory-dissipative energy; while endothermic action is commonly the reverse.

## THE CONDITIONS THAT DETERMINE THE INTERCHANGES

In a very broad sense, open conditions and freedom from pressure or other forms of restraint, favor exothermal reactions, while confinement and pressure favor endothermal reactions. Any form of crowding, even self-stress, naturally tends toward *divergence* of energy into the various paths available to it, since this affords relief. The higher the stress, the more it forces itself into unoccupied paths. Concentrative stress, therefore, favors the passage of a portion of the energy along endothermic lines and the formation of dense substances; while dispersive stress, low stress, and no stress, are less compulsory and give exothermic action freer scope. Apparently crowding is not confined to imposed stresses, but arises from what may be styled the self-stress of the activity. A small mass of gas in open space exerts little interior stress upon

[1] Compare C. K. Leith, "The Structural Failure of the Lithosphere," Vice-Presidential Address, Geol. Soc. Amer., *Science*, N.S., Vol. LIII (March 6, 1921), pp. 205–7.

itself, and only the larger vibrations are in evidence, but if the mass grows indefinitely the internal self-stresses increase and there appear in succession the shorter and more intense vibrations ranging up through the whole gamut of vibrations to the X-rays and doubtless beyond. There is, in this, increased pressure, of course, but the activity itself is increasingly *divergent* as well as increased in amount. However this may be interpreted, there is a growing complexity of vibration, and it seems to be a safe generalization that growing mass and growing internal pressure are attended by increase in the diversity of phases assumed by the compressional energy; in other words, there are more varied partitionings of the energy and it takes a larger number of paths, including more frequent interchanges between the endothermic and exothermic phases. As there is thus crowding in various directions for easement, the direction that gives greatest relief from the stress imposed by the environment naturally becomes a predominant trend. Where there is high pressure and it is unescapable, the line of relief is the passage of energy into a constructional form that gives additional density. Where the pressure is weak or absent, an expansional or dispersive form of energy may be more efficient in giving relief. Both forms are likely to be present and to co-operate with one another in any pronounced case.

## THE TESTIMONY OF PRESENT INTERNAL STATES AS TO THE DOMINANT DIRECTIONS TAKEN BY ENERGY IN THE INTERIOR

Tidal[1] and nutational[2] evidences concur in indicating a higher degree of rigidity and elasticity in the interior, taken as a whole, than in the outer shell. Seismic waves add very specific confirmatory evidence, so far as the outer seven-eighths of the volume of the earth is concerned. The seismic evidence for the remaining central part is as yet obscure, and is differently interpreted by the special students of the subject. In a general way, the whole of the interior is covered by the tidal and nutational evidences. These favor the interpretation of the central part as highly rigid and elastic, since

[1] A. A. Michelson and Henry G. Gale, "The Rigidity of the Earth," *Jour. Geol.*, Vol. XXVII (1919), pp. 585–601.

[2] W. Schweydar, "Die Elasticität der Erde," *Naturwissenschaften*, Part 38. Potsdam, Germany (1917).

these qualities fit the general import of the evidence, but for the present it is prudent to leave the question of the state of the center to be settled in the future. It is to be observed that the increasing density of the interior tends to dampen the speed of the seismic waves, and that correction for this effect must be made in deducing the inward increase of rigidity and elasticity from the seismic records. When allowance is made for this, the generalization that rigidity and elasticity are notably higher in the interior than in the outer shell is put beyond serious question. This means that in the partition of the compressional energy between those phases that increase the rigid elastic attachments of the molecules to one another and those phases that weaken or destroy these attachments, the former have been favored in a marked degree. This is testimony of a most cogent sort. By interpretation, this signifies that only a minor part of the compressional energy took the vibratory form in the interior, the major part taking the revolutional or constructive form, and that in doing this it served to promote compactness and the strength of hold of the constituents on one another.

### DID THE ORGANIZING ENERGY EFFECT CHANGES IN THE CONSTITUTION OF THE ATOMS?

Lest the seeming needs of the case bias us toward one conclusion rather than another, let us hasten to note that the mean density of the earth, compared with the probable density of the original matter, is such as to offer no real ground for bias in favor of atomic construction, for the higher density of the interior is fully accounted for by the density gradients that arise from metamorphism in the zone of observation. Atomic construction, if invoked as an aid, might as easily render the interior mass too dense, as to help explain the density as it is. Nor is there more than uncertain evidence bearing on the atomic question; but the matter is too important to be ignored in a discussion of the effects of compressional energy.

The most remarkable of known exothermal effects connected with rock-substance springs from the spontaneous atomic disintegration of the heaviest known elements. No evidence that this

disintegration has anything to do with relief of pressure, such as might be assigned to their rise from the interior, is now available. Any such possibility must be left to the revelations of the future. It is logically necessary, however, for one who believes in the indefinite cyclic persistence of the cosmos, to suppose that the present exothermic action is the reversal of an endothermic process that gave these elements the stores of energy they are now so persistently and systematically discharging. The place and time and conditions of this storing action are altogether open questions. By interpretation, the energy now being given out springs from intense revolutional action, for revolutional motion seems to be the only probable way in which such prodigious energies can be stored in so unobtrusive a state and given out so regularly and systematically and in such concentrated forms. The storing process must probably have involved somewhat similar forms and intensities of action. One of the most common speculations as to the place and conditions of this storage process, locates it in some center of great stress where pressure and heat co-operated. This should perhaps be amended by recognizing that the more intense vibratory agencies of the X-ray end of the series were even more probable agencies, because their motions were more nearly commensurate with the minute and swift revolutions that are supposed to store the energy in question. The center of the earth is possibly a place of the right type, but it belongs to an inferior order compared with the centers of stars, unless solidity counts for something. In this case the center of the earth might have a preferred place, since our planet is among the largest of known solid bodies. An alternative speculation places the origin of the radioactive substances in the outlying regions of space.

There is perhaps a suggestion of general atomic change in the remarkable phenomena of thermionic emission, contact potentials, and photoelectric action. These seem to imply that there is some kind of commensurability between the extremely intense oscillations of the vibratory activities and the orbital periods of the electrons, so that effective interaction and perhaps interchange takes place between them. Commensurability is perhaps the property by which interchange is effected between the minutely

vibratory and the minutely revolutional phases of energy. These speculative suggestions have little value beyond helping to make it clear that it is by no means safe to assume that atomic construction and destruction are not common functions of the interior.

## WHAT AMOUNT OF COMPRESSION IS IMPLIED BY THE MEAN DENSITY OF THE EARTH?

As already noted, there is no need to push appeal to the organizing functions of energy in the interior so far as to assume the building up of atoms for the sake of explaining the higher density of the earth's interior; indeed, if there is any constructive work of that sort, the increase above the decrease of density cannot go very far without making the mean density too great to fit the evidence. If we assume that the primitive matter had the meteoric density of 3.69 adopted by Farrington, and compare this with 5.53, the mean density of the earth adopted by Moulton, the mean increase in density due to compacting, reorganization, atomic change, etc., is only about 50 per cent. Or if, to assume an improbably low figure for the density of the earth's original matter, we take the moon's mean density, 3.34—assuming that the effects of compression at the moon's center are offset by the porosity of its outer part—the increase in the earth's mean density would be only a little over 65 per cent. In either case, or on any plausible assumption, some part of the compacting must be assigned to mechanical compression, so that the increase of density assignable to reorganization under the special conditions of the interior is not very large.

## THE INTIMATIONS OF THE DENSITY GRADIENT IN THE ZONE OF OBSERVATION

Geologists have been at great labor to compile thermal data from mines and deep borings that they might deduce from these a temperature gradient that would throw light on interior conditions, but the same line of attack on the rising density of the interior seems to have been overlooked. It is to be recognized, of course, that neither of these gradients can be projected to the center of the earth without reservation, for both curves probably fall off notably in the interior, but the density curve is probably as trustworthy a

guide as the temperature curve, for, in the planetesimal earth, both arise from compression and its direct and indirect consequences.

After an elaborate study of the most reliable data, Dr. H. S. Washington thus sums up his conclusions in a recent paper:[1] "I am inclined to place the average density of the crust at about 2.75 at least for the uppermost shell, while that of 2.80 would probably be nearer the truth for an average of any considerable depth, say 20 miles or more." The mean depths of these two shells can scarcely be more than 8 or 10 miles apart. The rise of density in this little difference of depth, if projected to the earth's center, would give a density there nearly twice that computed from the classic law of Laplace, or from the law of Roche specially formulated to meet the astronomical requirements. No account is here taken of mechanical compression, for the specific gravities adopted as the basis of the estimates were all taken under atmospheric pressure. Much less was any account taken of hypothetical quantities of metals or other specially heavy material, for both these shells are formed of common rock.

The two elements most common in the zone of observation, oxygen and silicon, often unite to form tridimite in the outermost shell but not in the plutonic rocks, where the same elements appear as quartz. This distribution is commonly assigned to differences in the physical conditions of the two horizons, especially differences in pressure. The specific gravity of tridimite ranges from 2.28 to 2.33, while that of quartz is 2.65. There is thus a rise of density of 15 per cent, so far as these minerals are concerned, between two horizons both of which lie in the limited zone made accessible by deformation and denudation.

The most instructive and suggestive data, however, are found in the progressive stages of increase in density developed in several different kinds of silts as they pass into various kinds of schists, and thence, in part, into a group of heavy minerals of which the garnets may be taken as types. The compression of the silts into shale may be neglected since a notable part of the increased density

[1] H. S. Washington, "The Chemistry of the Earth's Crust," *Jour. Franklin Inst.*, December, 1920, p. 804.

of the shale was due to the mechanical elimination of porosity. In forming the schists there was true reorganization with increased density, and still later there was further partial reorganization into much heavier minerals of the garnetic group. In the case of the garnets there is a rise in density from the schist minerals which formed them of 36 to 84 per cent, as pointed out by Van Hise.[1] In these cases the rise of density is unequivocally the result of the metamorphic reorganization of very common and representative kinds of material. It is to be noted further that one reorganization follows another even in this limited zone.

These specific cases show the possibilities and the actual tendencies to increase of density by metamorphism, quite apart from mechanical compacting. They point to the very significant fact that the chief density effects are to be sought in metamorphism rather than mere mechanical compacting by pressure. The crux of the compressional problem therefore lies in metamorphic reorganization, in selective liquefaction, and in the extrusion of magmas. The concrete task thus imposed is the tracing of the paths followed by the compressional energy and the study of the kind of work each phase of energy does. The specific phenomena to be explained are (1) the rising density, rigidity, and elasticity of the interior material; (2) such a distribution of density as to satisfy the intimations of the precession of the equinoxes and the nutation of the poles; (3) the amounts and kinds of diastrophism recorded in the structure of the earth; and (4) the protrusion and persistent maintenance of the continents and the complementary depression of the ocean basins, as well as the special configurations of the earth. It is not sufficient to explain these separately by isolated postulates. unless these are shown to be mutually compatible and connected with a common origin; these features are to be explained as a co-ordinate group of phenomena arising from a common origin and a common line of dynamic procedure.

## THE SPECIFIC PATHS OF THE COMPRESSIONAL ENERGY

In the following analysis, it is to be understood that the earth is assumed to be, and to have been at all stages after the formation

[1] C. R. Van Hise, *op. cit.*, pp. 205 ff.

of its collective nucleus, a solid body, built of heterogeneous planetesimal matter at the start, that it was subjected to a slowly growing gravitative pressure whose total accession was spread over a period of the order of two or three billion years, and that there were large allowances of time for metamorphism and for the adjustment of the strain arising from each increment of pressure. On these assumptions the chief partitions and paths of the compressional energy, seem logically to have been as follows:

The first step was the partition of the initial increment of energy by the passage of a part of the stress into strain, while another part took the thermal form. So long as the strain lasted, its energy was stored or latent. A varying but large measure of energy seems thus to have been stored all through the geologic ages. It appears from stratigraphic evidence that the strain-limit in the sub-surficial material has been high enough at several periods to permit the accumulation of stored energy sufficient to actuate declared deformative "revolutions" in spite of such partial easement as may have taken place, during the stages of accumulation, from the milder forms of idiomolecular action about to be described.

The second step in the compressive process was the co-operative action of the stored energy of strain and the agitative thermal energy. The latter aided change by loosening the fixed elastico-rigid attachments of the molecules, the essential properties that gave rigid symmetry to the crystals and solidity to the amorphous fragments. The hold of crystals and of clastic fragments upon their constituent molecules was unequal because some of them lay at the angles, or on the edges, or on sharp curves of the little masses, where fewer other molecules supported them. So also the strains arising from pressure upon the interlocking crystals or fragments was greatest on these outlying molecules. The particular molecules thus least securely held and those most severely strained, yielded first. This eased the strain on these particular points and threw the stress on new molecules; from this, new action of like order arose and the process was essentially repeated.[1]

[1] In many cases, especially near the surface, solution and chemical reaction greatly aided molecular transfer and crystalline reorganization, but these are accessory agencies rather than factors of the compressional process, as such.

The detached molecules of this first action, responding to such stress as was then felt by them in their relatively free state, took the lines of least resistance until they reached some point where the organizing force of some crystal, so situated as to be able to grow, brought them under control and reattached them with due orientation. Such reattachments were obviously conditioned by the balance of strength between the crystalline force and the weakest phase of the general pressure. As a result the growing crystal extended itself most in the line of least resistance and co-operated with other crystals of like situation in developing parallelism of structure.

It is obvious that such individual actions on the part of single molecules acting by themselves, and acted upon by special stresses, could take place while as yet the *general* strain was far below the strain limit and *general* detachment could not take place. If the pressure came on slowly enough, the whole crystal or fragment might be broken down in this piecemeal way while the general strain was below the mean strain-limit. As only a few molecules were in transit at any given time, the mass as a whole would remain solid throughout the process.

The action was thus the special work of individual molecules, each suffering its own strain and playing its own part in its own way, i.e., it was *idiomolecular*. The process is sharply distinguishable from the common movement of all molecules, such as usually takes place when liquids flow. The process may be studied to advantage in the granulation of snow at temperatures that inhibit liquefaction.[1]

So long as the stress and strain were mild, the foregoing action was obviously slow and had rather narrow limitations. But with notable increase of stress, giving rise to increase of strain, and increase of heat, the process appears to have been hastened and given a tendency to collective action in parallel lines, planes, or belts, doubtless because resistance was less effective against such

[1] C. S. Peet and E. C. Perisho, working with the writer in the winter of 1894, found by daily micrometric measurements of many granules, that the larger ones grew every day whether the temperature was at, above, or below 0° C., the growth apparently taking place at the expense of the smaller, more sharply curved granules.

united action. This apparently went so far in some cases as to verge toward general simultaneous molecular action, but analysis seems to show that it remained idiomolecular in actual method. From such quasi-collective but really idiomolecular action, cleavage, schistosity, and other forms of structural parallelism arose. In glaciers this idiomolecular type of action seems to range from snow granulation to the point where fracture takes place and the movement becomes a massive shear.[1]

By further increases of pressure, the strain limit *along selected lines* was reached and definite fracture and shear took place, or else the whole mass was crushed to fragments. In either of these cases, the action became diastrophic rather than metamorphic.

It has been very generally held that when such depths and pressures are reached as to inhibit fracture, general movement of the molecules over one another after the manner of liquids must take place. The original idea of "rock flow" seems to have sprung from this notion. In a highly rigid body, such a general movement of molecules upon one another requires the breakage of all the bonds between molecule and molecule and so *involves a maximum of force.* Moreover, this force must come from *differential* stress, since *balanced* stress, within limits, forces the molecules into closer and stronger relations. The supposed "flow" seems improbable except when true liquidity, which destroys the special rigid bonds of the solid state, is brought about. So far as differential stresses affect the solid matter of the interior, easement by idiomorphic action, either collective or isolated, seems to require much less energy and is hence more probable. With the open structure now assigned matter, and with the abundant evidence that molecules really collect into crystals in the midst of rock that seems quite solid, and with other phenomena giving evidence that in some way molecules creep through solid matter, there seems no substantial ground for excluding idiomolecular action from the deep interior.

[1] It was from the study of the granulation of snow, the growth of glacial granules, and the development of schistosity in the glaciers of Greenland, in 1894, that the method and importance of this individual action of molecules, while the mass remained solid, was first realized by the writer. "Glacial Studies in Greenland," Presidential Address, *Geol. Soc. Amer.*, Vol. VI (1895), pp. 209–14.

In tenacious solids where impact takes place at high velocities and with prodigious force, as in the case of a steel target struck by a solid shell, there is no time for idiomolecular action, and very little for any form of selective or metamorphic action, and so all molecules are apparently caused to move over one another in a way that is scarcely distinguishable, if at all, from real flow. The slowness of the increases of stress in the interior of the earth, however, is thought to put deep-seated diastrophism in a quite different category from this velocity-stress action.

Although fluidal action is placed in a secondary order in the evolution of a planetesimal earth, the formation and extrusion of magmas play a very important function in its compression, but that must be left for a later article.